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**Abstract**
The early validation of a 20 year service integrity for the bonded interfaces in low cost solar arrays is an important requirement in the Low Cost Solar Array ( LSA) project. An atmospheric corrosion model has been developed and verified by five months of corrosion rate and climatology data acquired at Mead, Nebraska LSA test site. Atmospheric corrosion monitors (ACMs) installed at the Mead test site showed that protection of the corroding surface by the encapsulant is achieved independent of climatology variations. A newly designed Mead climatology simulator has been developed in laboratory corrosion studies to clarify corrosion mechanisms displayed by two types of LSA modules at the Mead test site. Controlled experiments with identical moisture and temperature aging cycles showed that UV radiation causes corrosion while UV shielding inhibits LSA corrosion. The implementation of AC impedance as a NDE monitor of environmental aging in solar cell arrays has also been demonstrated.

**Keywords**
Nondestructive Evaluation

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Materials Science and Engineering

# STUDY PROGRAM FOR ENCAPSULATION MATERIALS INTERFACE FOR LOW-COST SOLAR ARRAY (LSA)

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## ABSTRACT

The early validation of a 20 year service integrity for the bonded interfaces in low cost solar arrays is an important requirement in the Low Cost Solar Array (LSA) project.

An atmospheric corrosion model has been developed and verified by five months of corrosion rate and climatology data acquired at Mead, Nebraska LSA test site. Atmospheric corrosion monitors (ACMs) installed at the Mead test site showed that protection of the corroding surface by the encapsulant is achieved independent of climatology variations.

A newly designed Mead climatology simulator has been developed in laboratory corrosion studies to clarify corrosion mechanisms displayed by two types of LSA modules at the Mead test site. Controlled experiments with identical moisture and temperature aging cycles showed that UV radiation causes corrosion while UV shielding inhibits LSA corrosion.

The implementation of AC impedance as a NDE monitor of environmental aging in solar cell arrays has also been demonstrated.

## MEADCLIMATOLOGY AND CORROSION MONITORS

Two atmospheric corrosion monitors (ACM) were installed at the Mead, Nebraska site. One corrosion sensor is bare so as to represent a corrosion response in the absence of encapsulated protection. The second corrosion cell is covered with 2 mm SYLGARD 184 encapsulant over a reactive primer GE-SS4155. The output of the corrosion monitors is connected into the data acquisition system at Mead. Inspection of Fig. 1 shows that the unprotected ACM corrosion current rises and falls as a direct function of both relative humidity (RH) or moisture supersaturation temperature ($T_D$-T) during high moisture conditions. Conversely, precipitation produces no special corrosion response not already related to atmospheric moisture saturation level.

The curves of corrosion current ($\log_{10}$ I) versus supersaturation temperature. ($T_D$-T) shown in Fig. 2 clearly indicate the reversible transition in corrosion rate with level of moisture supersaturation for two cycles of condensation and subsequent surface drying.

A corrosion model has thus been developed, as shown in Fig. 3. The model relates the condensation probability, $P_c$, to the magnitude of the diffusion controlled corrosion current, I. As shown in Fig. 2, with increasing supersaturation temperatures ($T_D$-T), the corrosion current displays an upper limiting current I ≃ 15 μA. Referring to Fig. 3, this upper limiting current refers to the condition where condensation probability $P_c$ = 1.0 and the current equals the limiting diffusion current $I = I_L$.

## MEAD CLIMATOLOGY SIMULATOR

The laboratory apparatus constructed to achieve Mead corrosion simulation is shown in Fig. 4(A). This table mounted apparatus consists of two Haake Type K41 thermal regulators (-20°C to 100°C) with liquid circulation. The rear Haake unit circulates thermostatted liquid to the rear copper surface of the corrosion cell, as shown in Fig. 4(B). The liquid temperature of this rear Haake unit and the corrosion cell face is programmed to follow the 3 hour cycles of alternate $T_1$ = 344K and $T_2$ = 268K as shown in Fig. 5 by the cam driven West controller affixed to the lower front table surface. The front Haake unit is set at constant elevated temperature $T_3$ > 307K for conditioning the alternating moist (100% RH) and dry (≃ 0.016 RH) air streams which pass through the corrosion cells. A time selector valve set for six hour intervals switches the air stream from moist to dry air every six hours.

Figure 4(B) shows a close-up view of the corrosion cell. In this view two Solarex cells are thermally attached to the copper back plate of the corrosion cell using thermally conductive thermocote joint compound. The upper Solarex test cell is covered by opaque aluminum foil to prevent direct irradiation by a medium pressure mercury arc lamp.

The different aging effects produced by one month of continuous exposure in the Mead corrosion simulator are shown in Fig. 6. Figure 6(A) shows four encapsulated Solarex solar cells. The upper two Solarex cells were aged in the Mead simulator for one month with the right cell exposed to UV and the left cell shielded from UV. The lower two Solarex cells were cut from a panel aged at Mead for approximately two years. Inspection of Fig. 6(A) shows that the upper right Solarex cell which was exposed to UV irradiation in the Mead simulator, shows the characteristic staining of the metallized collector as shown by the lower two Solarex cells with two years Mead site exposure. The UV protected Solarex (upper left) retains the metallic luster on all metallized areas indicative of corrosion inhibition by UV protection.

Figure 6(B) shows four Sensor Tech solar cells aged in the Mead simulator for one month. The two left Sensor Tech cells were shielded from UV exposure while the two right cells were exposed to UV. A point source of light focused on the solar cells from near the camera lens shows the higher level of light reflection and loss of efficiency of the anti-reflection coating in the UV exposed right Sensor Tech cells. This loss of anti-reflection efficiency and bleaching of anti-reflection coating of the Sensor Tech cells is a prominent aging characteristic shown for Sensor Tech modules aged naturally at the Mead test site.

The solar cells shown in Fig. 6 were continuously monitored while in the Mead simulator for photovoltaic responses as well as front and back face temperatures. These data were recorded on the multichannel printing recorder shown in the center of Fig. 4(A). Three typical temperature traces recorded by the simulator over a six hour control cycle are shown in Fig. 7. The upper and lower curves of Fig. 7 show the recorded analog signals of short circuit current for the respective UV exposed (upper) and UV shielded (lower) Sensor Tech solar cells. The three temperature curves of Fig. 7 show good heat transfer at the solar cell back surface and maximum thermal gradient through the cell thickness to 10-12°C at the simulation temperature extremes.

AC impedance tests were conducted at various points in the one month Mead exposure experiments. The data summary of Table 1 shows the effects of one month Mead simulation on AC impedance properties. The UV shielded Solarex test cell is unchanged in the AC impedance properties while UV exposure results in a measured increased in shunt resistance. The capacitance of both UV increased by Mead simulation aging while shunt resistance values are only lightly diminished as in lower Table 1. Sensor Tech solar cells are shown in Table 1 to display much higher shunt resistance values than the Solarex solar cells.

## CORROSION MECHANISMS AND MATERIAL RECOMMENDATION

Auger electron spectroscopy (AES) has been used to determine the composition of the interfacial region between the encapsulant and the solar cell. To perform the AES analysis, the encapsulant was removed from the support materials, as shown in Fig. 8.

Auger analysis was performed both on the surface as removed and also after sputtering to various depths by argon ion bombardment. An example of the type of spectra obtained is shown in Fig. 9 and 10. Figure 9 is a spectrum taken from the silicon surface of a virgin Sensor Tech cell. The $SiO_x$ anti-reflection coating is observed as well as P, C, Sn and Na. Figure 10 is the spectrum taken after 60 Å has been removed by sputtering. Only $SiO_x$ is observed indicating that the contaminating species are only several monolayers thick.

No environmental contaminants were detected on the silicon surface of the Solarex cells which were aged at Mead. Carbon was observed throughout the $Ta_2O_5$, resulting from the deposition process. However, the metallization of these cells had a layered structure. The upper layer, approximately 50 Å in thickness, was a mixture of silver chloride and silver sulfide. Beneath this salt layer there was a 300 Å layer rich in silver but also containing moderate amounts of sulfur and chloride. The silver-rich layer as well as the $Ta_2O_5$ coating contained large amounts of iron. These layers were on top of the $Ta_2O_5$ anti-reflection coating. Figure 11 shows the Auger spectrum from the surface of the salt layer; Fig 12 is the spectrum after 300 Å have been removed by sputtering.

## SUMMARY

1. An atmospheric corrosion model has been developed. The model predicts the corrosion rate as controlled by surface condensation and diffusion limited currents.

2. A Mead site climatology simulator has been developed to reproduce Mead climatology at 3 hour cycles with in situ AC impedance and I-V monitoring of single cells.

3. Two independent, materials related corrosion mechanisms have been identified for Sensor Technology and Solarex cells.

## ACKNOWLEDGEMENT

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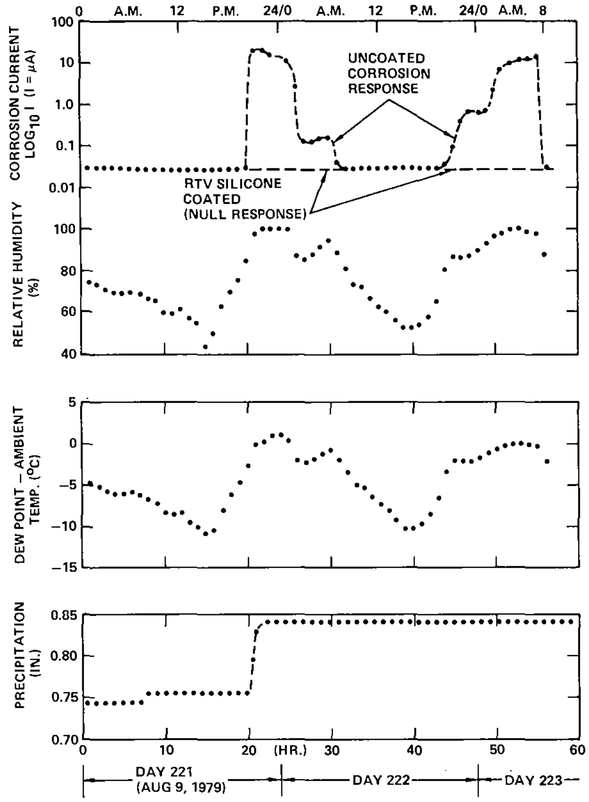


Fig. 1 Mead site moisture and rain climatology.

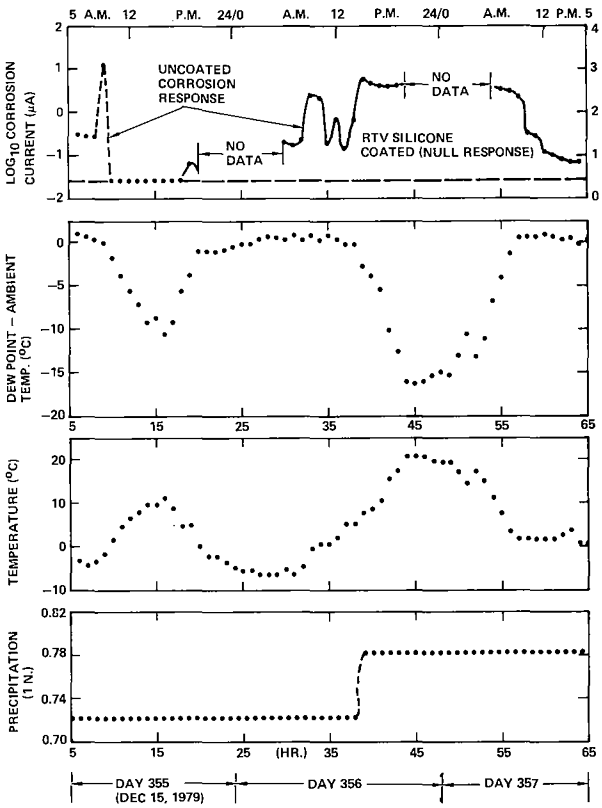


Fig. 2 Mead site freeze-thaw climatology.

(1) CONDENSATION PROBABILITY ($P_C$):

$$P_C = \frac{I}{I_o} = \exp\left[\frac{-1.756 \cdot 10^{22} \cdot \phi \cdot \nu^2 \cdot \gamma_{LV}^3}{T^3 (\ln P/P_o)^2}\right]$$

WHERE
- $\phi$ = WETTABILITY PARAMETER
- $\nu$ = WATER MOLAR VOLUME
- $\gamma_{LV}$ = LIQUID-VAPOR SURFACE TENSION
- $T$ = KELVIN TEMPERATURE
- $P$ = LIQUID VAPOR PRESSURE
- $P_o$ = SATURATED LIQUID VAPOR PRESSURE
- $I$ = RATE OF CONDENSATION (DROPS/$M^3S$)
- $I_o$ = MAXIMUM RATE OF CONDENSATION

(2) DIFFUSION CONTROLLED CORROSION:

$$I = P_C \cdot I_L = P_C \cdot \frac{nFDC}{\delta t}$$

WHERE
- $I$ = CURRENT DENSITY (AMPERES/$M^2$)
- $I_L$ = LIMITING CURRENT DENSITY
- $n$ = NUMBER OF ELECTRONS
- $F$ = FARADAY (96500 COULOMBS/EQUIVALENT)
- $D$ = DIFFUSION COEFFICIENT OF REDUCING ION
- $C$ = CONCENTRATION OF DIFFUSING IONS (MOLES/$M^2$)
- $\delta$ = DIFFUSION LAYER THICKNESS ( $\simeq 5 \times 10^{-4}$M IN STATIC SOLUTION)
- $t$ = TRANSFER NUMBER OF ALL IONS IN SOLUTION ( $\simeq$ 1.0 IF MANY OTHER IONS PRESENT)

Fig. 3 Corrosion model

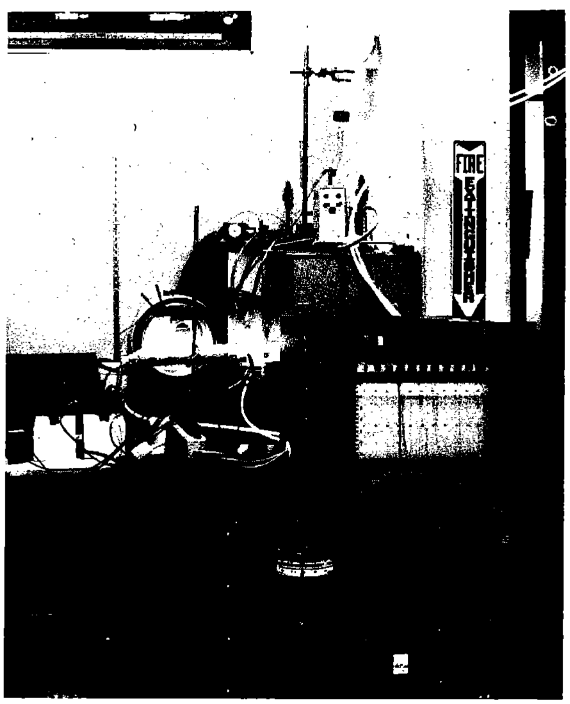


Fig. 4(A) Photoview of Mead corrosion simulator.

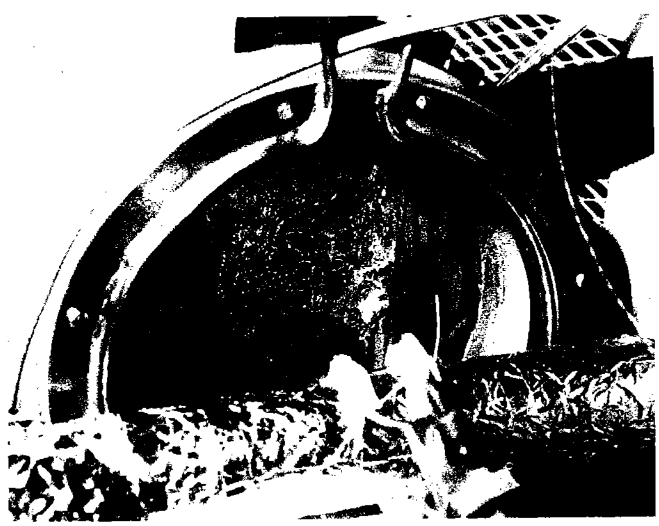

Fig. 4(B) Close view of corrosion cell with UV protected (upper foil covered) and UV exposed Solarex cells.

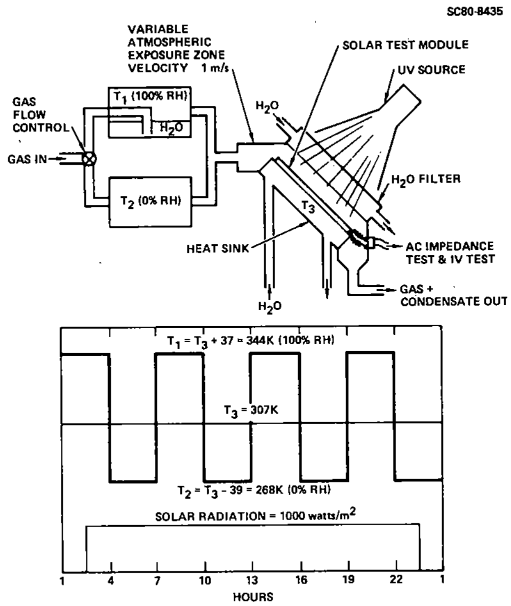


Fig. 5 Environmental solar test cell.

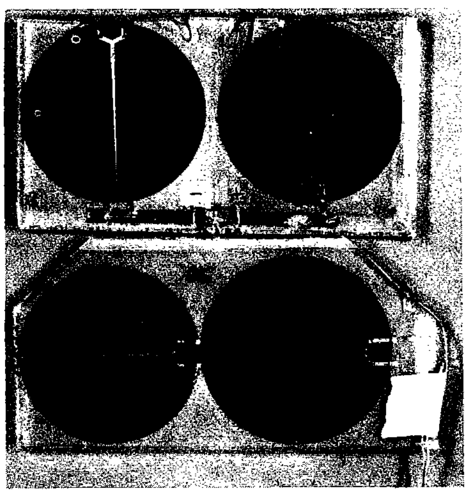

Fig. 6(A) Solarex solar cells subjected to lab simulation aging (top two with left UV protecter and right UV exposed) and Mead aged (lower 2 cells).

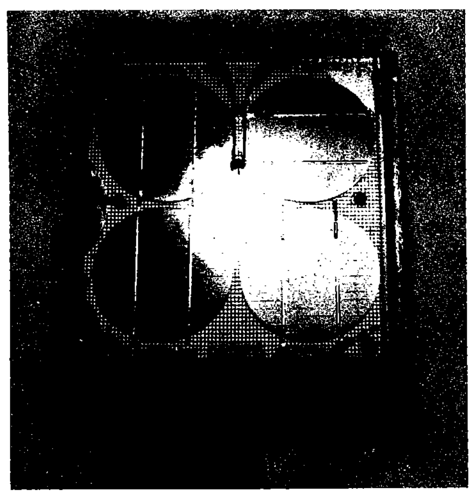

Fig. 6(B) Sensor Tech cells subjected to lab simulation aging with UV protection (left two) and UV exposed (right two).

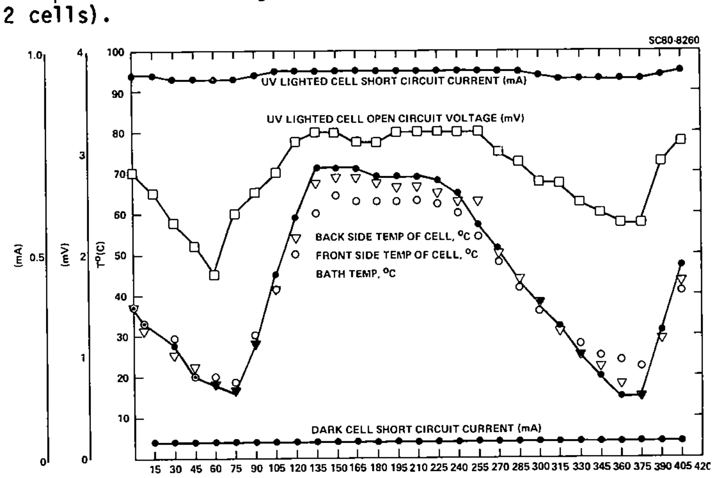


Fig. 7 Monitoring of Sensor Tech 2-cell series response in Mead corrosion simulator for a typical 7.5 hr cycle.

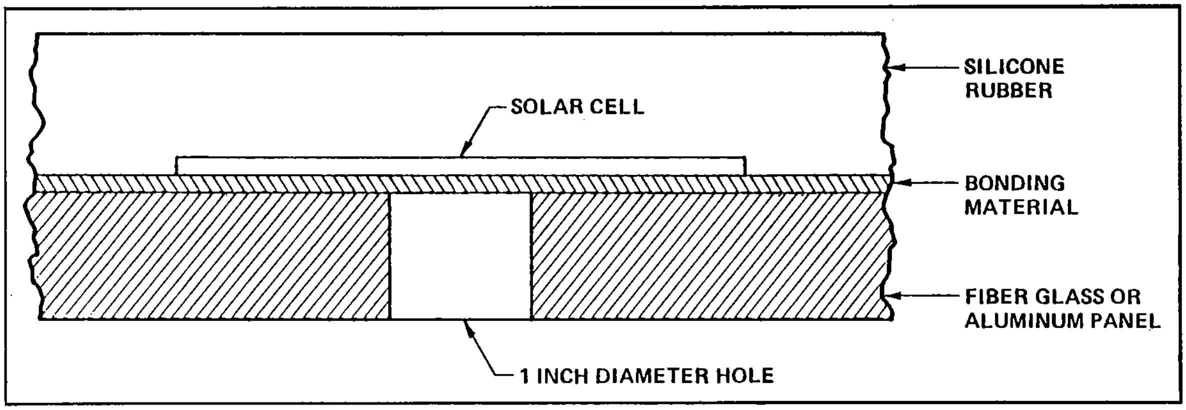


Fig. 8 Removal of silicone rubber for AES.

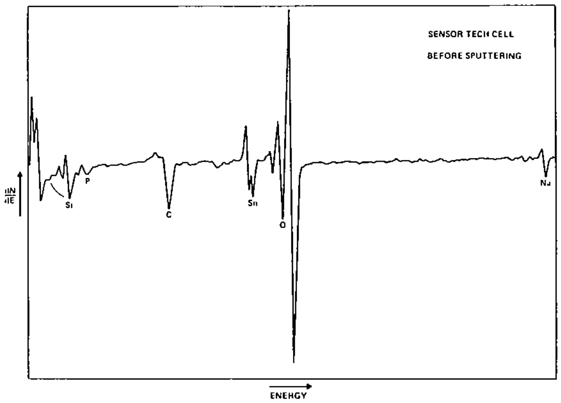


Fig. 9 Auger spectrum of silicon surface of unaged Sensor Tech module No. 5064.

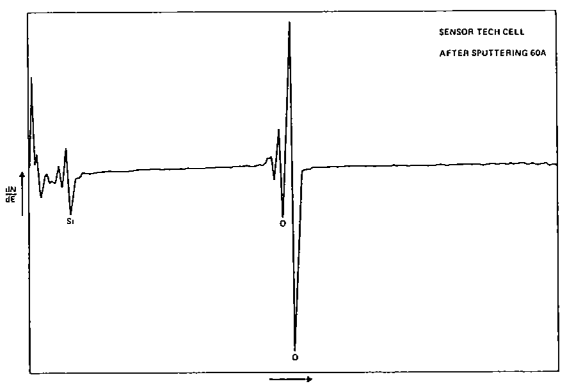


Fig. 10. Auger spectrum of sputtered (60A) silicon surface of unaged Sensor Tech module No. 5064.

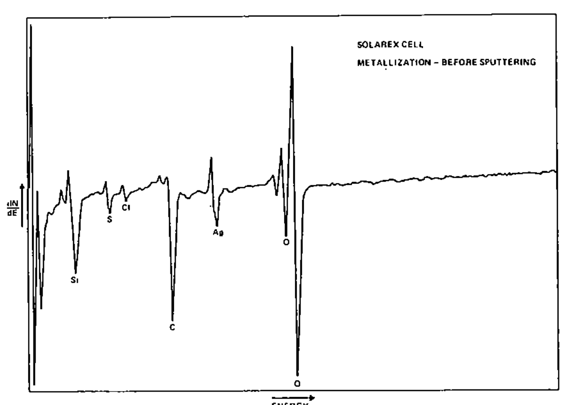


Fig. 11 Auger spectrum of metallization surface of Mead aged Solarex module No. 0217155.

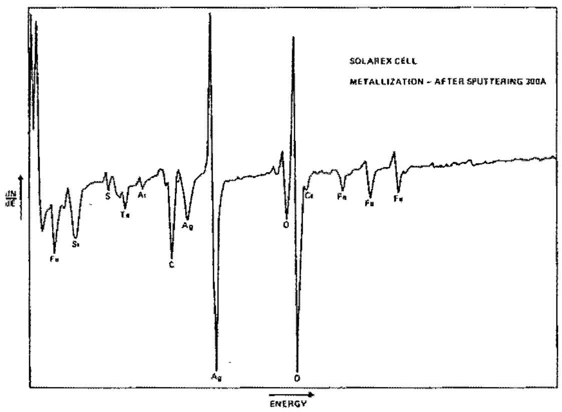


Fig. 12 Auger spectrum of sputtered (300A) metallization of surface of Mead aged Solarex module No. 0217155.

Table I

Mead Simulator Aging Effects on AC Impedance Response
(Tested in Ambient Lab Illumination)

| Specimen | $R_{sh}$ (ohm) | $R_s$ (ohm) | C (μF) |
|---|---|---|---|
| Solarex UV shielded (single cell) | | | |
| unaged | 25.5 | 1.0 | 1.48 |
| one month Mead simulator | 25.8 | 1.0 | 1.47 |
| Solarex UV exposed (single cell) | | | |
| unaged | 40.8 | 1.0 | 1.53 |
| one month Mead simulator | 47.2 | 1.0 | 1.50 |
| Sensor Tech UV shielded (2 cells in series) | | | |
| unaged | 368 | * | 0.21 |
| one month Mead simulator | 365 | * | 0.30 |
| Sensor Tech UV exposed (2 cells in series) | | | |
| unaged | 540 | * | 0.21 |
| one month Mead simulator | 522 | * | 0.27 |

*Small value, below detection capability